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Bimodal Brightness Oscillations in Models of Young Binary Systems

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Abstract

We consider a model for the cyclic activity of young binary stars that accrete matter from the remnants of a protostellar cloud. If the orbit of such a binary system is inclined at a small angle to the line of sight, then the streams of matter and the density waves excited in the circumbinary disk can screen the primary component of the binary from the observer. To study these phenomena by the SPH (smoothed particle hydrodynamics) method, we have computed grids of hydrodynamic models for binary systems based on which we have constructed the light curves as a function of the orbital phase.The main emphasis is on investigating the properties of the brightness oscillations. Therefore, the model parameters were varied within the following ranges: the component mass ratio $q = M_2 : M_1 = 0.2 - 0.5$ and the eccentricity $e = 0 - 0.7$. The parameter that defined the binary viscosity was also varied. We adopted optical grain characteristics typical of circumstellar dust. Our computations have shown that bimodal oscillations are excited in binaries with eccentric orbits, provided that the binary components do not differ too much in mass. In this case, the ratios of the periods and amplitudes of the bimodal oscillations and their shape depend strongly on the inclination of the binary plane and its orientation relative to the observer. Our analysis shows that the computed light curves can be used in interpreting the cyclic activity of UX Ori stars.

Key words: *variable stars, binary stars, early evolutionary stages*.

1 INTRODUCTION

The circumstellar extinction variations due to an inhomogeneous structure of the circumstellar gas– dust disks are among the causes of the photometric variability of young stars. This variability mechanism dominates in UX Ori stars, because their circumstellar disks have an "optimal" orientation at which the line of sight "touches" the surface of the disk or, more precisely, passes through its inhomogeneous gas–dust atmosphere (Grinin et al. 1991). For such a disk orientation, the current brightness state of the star is determined by the amount of dust on the line of sight at the time of its observation. The amount of dust on the line of sight changes continuously due to the differential rotation of the matter in the disk, which has an effect on the stellar brightness.

Analysis of long series of photometric observations shows that apart from irregular circumstellar extinction variations, many stars of this type also exhibit wavelike (cyclic) variations with characteristic time scales from several to ten or more years (Shevchenko et al. 1993; Grinin et al. 1998; Rostopchina et al. 1999; Herbst and Schevchenko 1999; Bertout 2000; Shakhovskoi et al. 2005). In some cases, there are simultaneously two cycles with different periods in the light variations of UX Ori stars.

Cyclic photometric variability reflects the presence of large-scale gas–dust structures in the circumstellar disks. Grinin et al. (1998) and Rostopchina et al. (1999) put forward the idea that the density waves and the streams of matter attributable to the presence of a secondary component or a protoplanet are such structures. Their existence is predicted by the hydrodynamic models of young binary systems computed by Artymowicz and Lubow (1996). The computations of these authors showed that a matter free gap is formed in the central part of a young binary system under gravitational perturbations. Its size depends on the component mass ratio of the binary and its orbital eccentricity. Under viscous forces and gravitational perturbations, two streams of matter generally unequal in intensity penetrate this gap; they maintain the accretion activity of the components and produce accretion disks around each of them.

The hydrodynamic computations by Sotnikova and Grinin (2007) showed that three types of extinction variations could arise on the line of sight in young binary systems accreting matter from the remnants of a protostellar cloud and inclined at a small angle to the line of sight. The shortest period P_1 is equal to the orbital one and is produced by the streams of matter that periodically penetrate from the circumbinary disk into the binary and cross the line of sight. The second period P_2, which is approximately a factor of 5–8 longer than the orbital one, is produced by the motion of a one-armed density wave in the circumbinary disk. The third period P_3 is attributable to slow precession of the circumbinary disk and is equal to several hundred orbital periods.

In this paper, we study in detail the properties of the first two oscillation modes. For this purpose, we computed a family of hydrodynamic models for young binary systems by the SPH method. Based on these models, we constructed the light curves and investigated the influence of the model parameters of young binary systems on the properties of the first two periods. The results of our analysis are discussed in the context of the cyclic activity of UX Ori stars.

2 THE COMPUTATIONAL METHOD

We computed the hydrodynamic flows and density waves in a young binary system using the SPH algorithm described in detail by Sotnikova and Grinin (2007). The mass of the

circumbinary (CB) disk was assumed to be low compared to the total mass of the stars in the binary system, which allowed the disk self-gravity to be neglected.We also assumed that the disk was isothermal and that the dust was well mixed with the gas. It should be noted that using the isothermal approximation in our case is justifiable, because the density perturbations in a comparatively narrow region of the CB disk, near its inner boundary, make a major contribution to the extinction variations on the line of sight. This allows the sizes of the domain of integration in the SPH method to be limited by a radius of $20\,a$, where a is the semimajor axis of the orbit at eccentricity $e = 0$.

For each model, we computed the column density of test particles toward the primary component of the binary as a function of the orbital phase. As a rule, the computations were performed for several hundred orbital periods. This time interval is shorter than the characteristic CB-disk dissipation time attributable mainly to the accretion of matter onto the binary components by a factor of several (Sotnikova and Grinin 2007).

For the models computed in this way, we passed from the column density of test particles to that of real grains.We began our quantitative analysis of the computational results with the removal of the trend in the column density variations attributable to the decrease in the number of test particles in the binary as a result of their accretion onto its components. The trend was modeled by a fifth-degree polynomial. Our computations showed that this ensured a satisfactory removal of the trend for all of the models considered. Next, we performed a Fourier analysis of the time series freed from the trend with the calculation of the likelihood function with a probability $p = 0.99$ (Vityazev 2001). In this way, we revealed the cycles of the model time series for the column density. The period P_2 was determined from the centroid of the corresponding peak in the Fourier spectrum.

To construct the bimodal light curves, we chose a fragment of the particle column density variations with a duration of $2\,P_2$ in each model. To reduce the influence of fluctuations, we used the method of a three-point moving average. The optical depth of the dust layer on the line of sight should be determined to pass from the column density of test particles to magnitudes, which requires passing from the test particles to real grains. This was done as follows: first, we determined the "weight" of a single test particle. For this purpose, we specified the accretion rate onto the binary components $\dot{M}_a$ as a parameter of the problem and compared this quantity with the accretion rate of test particles determined during the computations (for more detail, see Sotnikova and Grinin 2007). Below, in our calculations, $\dot{M}_a$ was taken to be $10^{-10}\,M_{\odot}$, which is approximately an order of magnitude lower than the typical accretion rates onto UX Ori stars (Tambovtseva et al. 2001; Muzerolle et al. 2004). Our calculations showed that for the orbital inclinations for which these were performed, such an accretion rate is sufficient to produce a strong modulation of the brightness of the primary component in the binary.

The mass of a single particle was calculated as follows:

$$m_d = \frac{P\,\dot{M}_a}{N} \tag{1}$$

where P is the orbital period, N is the total number of test particles accreting on both components in one binary revolution, and $\dot{M}_a$ is the adopted accretion rate.

The area of the column section s is a technical parameter of the problem. It was specified as $s = 2h \times 2h$, where $h = 0.1\,a$. Our calculations showed that this value of s is optimal for the solution of the formulated problem (at lower values of s, the influence of fluctuations is enhanced; at its higher values, the time resolution of the calculated characteristics deteriorates). Thus, having calculated the mass of a single test particle, we obtain the matter column density in units of g/cm^2. Now, the opacity κ per gram of matter should be taken as

a parameter of the problem to determine the optical depth of the dust on the line of sight. This parameter depends on the type and sizes of the dust grains and on the dust-to-gas mass ratio. The latter is commonly assumed to be the same as that, on average, in the interstellar medium: 1 : 100. The typical circumstellar dust extinctions in the optical spectral region lie within the range $\kappa = 100 - 300\,cm^2/g$ (see, e.g., Natta and Whitney 2000). In our calculations, we adopted $\kappa = 250\,cm^2/g$, which corresponds to the maximum of the Johnson B passband. Multiplying the matter column densities calculated in this way by κ, we will obtain the optical depths τ for each instant of time.

It should be noted that the intensity of the radiation from young stars generally consists of two parts: the intensity of the stellar radiation I_* (in our case, the primary component of the binary) attenuated by a factor of $e^{-\tau}$ and the intensity of the radiation scattered by circumstellar dust I_{sc}:

$$I_{obs} = I_* e^{-\tau} + I_{sc}\,, \tag{2}$$

The contribution of the scattered light to the observed radiation from young stars typically does not exceed a fewpercent (the young HH 30 stars whose direct radiation is severely attenuated by absorption in their circumstellar disks seen edge-on constitute an exception). Therefore, below, when studying the pattern of variability in the primary component of the binary, we took the intensity of the scattered radiation in (2) to be zero. The light variations of the primary component are expressed in magnitudes: $\Delta m = -2.5 \cdot lg\, I_{obs}$ (I_* is taken as unity).

3 RESULTS

We computed theoretical light curves for binary systems by the method described above. The basic model parameters are given in the table. In all models, the mass of the primary component is $2\,M_\odot$, a value typical of many UX Ori stars (Rostopchina 1999); M_2 is the mass of the secondary component; c is the dimensionless speed of sound in the matter expressed in units of the orbital velocity of the secondary component at $e = 0$. The number of test particles is $N = 60000$ and the smoothing length is $h = 0.1a$. The orbital period is taken to be five years. For a circular orbit, its radius is $3.7AU$. The last column of the table gives the values of the period P_2 calculated by the method described above and expressed in units of the orbital period.

The model parameters were varied within the following ranges: the component mass ratio $q = M_2/M_1 = 0.1 - 0.5$ and the eccentricity $e = 0 - 0.7$; the dimensionless speed of sound in the CB disk c appearing in the expression for viscosity was taken to be 0.02 ("cold" disk), 0.05 ("warm" disk), and 0.08 ("hot" disk). Our computations were performed for several inclinations of the equatorial plane of the binary system to the line of sight and four positions of the apsidal line relative to the observer (with a 90° step). The choice of inclinations was restricted by a finite number of test particles and the necessity of avoiding great statistical fluctuations in the number of particles on the line of sight.

Figures 1–4 present the bimodal light curves of a binary system for different positions of the apsidal line relative to the observer and two inclinations of the disk plane to the line of sight.We see that when the orbital orientation changes relative to the observer, the light curve can change significantly. First, the shape of the light curves changes with position of the apsidal line and with orbital inclination. Second, the relationship between the fast and slow oscillation modes changes.

The dependence of the light curves on the orbital inclination is quite understandable if we take into account the fact that the streams of matter propagating from the CB disk to the central part of the binary system contribute to the extinction variations with orbital phase, while the period P_2 is produced by the motion of a one-armed density wave in the CB disk. For this reason, the contribution of this wave to the extinction variations is more sensitive to changes in the inclination and decreases rapidly as it increases.

The strong influence of the position of the apsidal line on the light curves is caused by a global asymmetry of the CB disk (for its origin, see Artymowicz and Lubow1996). The azimuthal dependence of the geometrical thickness of the inner CB disk region (Sotnikova and Grinin 2007) results from this asymmetry. It is this factor that is responsible for the strong dependence of the binary's light curves on the position of the apsidal line.

In models 1–3 and 7, we varied the orbital eccentricity. In model 7 ($e = 0.1$), there is no slow oscillation mode with the period P_2. As e increases from 0.3 to 0.7, the second period appears. In this case, the ratio P_2/P_1 increases with e: $P_2/P_1 = 4.73 \pm 0.07$ in model 1, 5.93 ± 0.06 in model 2, and 6.77 ± 0.14 in model 3. This dependence of the slow oscillation mode on e can be explained as follows: the radius of the inner gap in the CB disk increases with orbital eccentricity (Artymowicz and Lubow 1994) and since the one-armed density wave propagates with a velocity close to the Keplerian one, increasing e reduces the velocity of its propagation over the CB disk.

We used models 2, 5, 6, and 9 to analyze the influence of the binary component mass ratio on the period ratio. Our computations showed that the amplitude of the slow oscillation mode became vanishingly small as q decreased; the period itself P_2 also decreased: in model 9 with the mass ratio $q = 0.1$, there is no second period; the period ratio is 5.19 ± 0.16 in model 6 ($q = 0.2$), 5.93 ± 0.06 in model 2 ($q = 0.35$), and 6.56 ± 0.1 in model 5 ($q = 0.5$). This dependence of the period P_2 on the mass of the secondary component is caused by the same factor as that for the dependence of P_2 on eccentricity e: the size of the inner gap in the CB disk increases with mass of the secondary component (Artymowicz and Lubow,1994), causing the angular velocity of the density wave in the CB disk to decrease.

In models 4, 5, and 8, we varied the parameter c, the dimensionless speed of sound in the matter that characterizes the disk viscosity. Our computations showed that the period P_2 reached its maximum at $c = 0.05$. The period ratio is $P_2/P_1 = 5.97 \pm 0.01$ in model 4 ($c = 0.08$), 6.56 ± 0.10 in model 5 ($c = 0.05$), and 5.43 ± 0.11 in model 8 ($c = 0.02$). In this case, the slow oscillation mode gradually degrades with decreasing viscosity.

The results listed above were obtained without taking into account the effect of scattered radiation. Nevertheless, these are also valid in real systems with a noticeable contribution of scattered light. This can be seen from Fig. 5, which shows two light curves. These were computed at $I_{sc} = 0$ and $I_{sc} = 0.1\, I_*$. We see that the scattered radiation reduces the amplitude of the brightness oscillations, but their bimodal structure is retained.

To conclude this section, the following should be noted: in counting the number of test particles on the line of sight, we had to limit ourselves to a small range of orbital inclinations relative to the line of sight ($\leq 10°$), since the influence of statistical fluctuations

4 DISCUSSION AND CONCLUSIONS

The results presented above show that the streams of matter and the density waves produced in a young binary system by periodic gravitational perturbations are capable of causing appreciable (in amplitude) periodic extinction variations, which can lead to cyclic light variations in young stars. The amplitude and shape of the light curves depend significantly

on the binary parameters (component mass ratio, orbital eccentricity, and disk viscosity), the accretion rate, and the binary orientation in space. The latter includes not only the inclination of the orbital plane to the line of sight but also its orientation (for a noncircular orbit) relative to the observer.

Our computations showed that two different cycles could be simultaneously present in the light variations of the binary's primary component in a fairly wide range of model parameters: one of them corresponds to the orbital period and the other corresponds to the revolution period of a one-armed density wave near the inner CB disk boundary. The period ratio P_2/P_1 depends on the binary parameters. It follows from the table that in five of the seven models in which both oscillation modes are simultaneously present, the period of the second mode (expressed in fractions of the orbital period) is close to an integer (5, 6, or 7). This suggests that the Lindblad resonance closest to the inner CB disk boundary plays an important role in forming the slow cycle.

The amplitude of the brightness oscillations with the period P_2 decreases with decreasing mass of the secondary component and becomes vanishingly small at $q \leq 0.1$. It also decreases as one passes from eccentric orbits to circular ones. Viscosity also has a significant effect on the amplitude of both oscillations.

In the Introduction, we pointed out that the cyclic activity of UX Ori stars is related to the extinction variations presumably caused by the presence of massive perturbing bodies (protoplanets, brown dwarfs, binary components) in their neighborhoods. Observations show that the amplitude of the cyclic component in the light variations of these stars ranges from several tenths of amagnitude to two magnitudes in the V band, i.e., it is comparable to the theoretical values at a binary inclination of about 10° (Figs. 1–4). In fact, the circumstellar disks of UX Ori stars are inclined relative to the line of sight at slightly larger angles (see Natta andWhitney 2000). However, the accretion rate for these stars is $10^{-8} M_{\odot}/yr$ (Tambovtseva et al. 2001; Muzerolle et al. 2004), i.e., it is higher than that in the models computed above by a factor of 100. This suggests that the photometric cycles can also be observed at binary inclinations exceeding 10° (see the previous section).

As was pointed out in the Introduction, two component cycles were detected in some of the UX Ori stars. In particular, for SV Cep (Rostopchina et al. 1999) and CQ Tau (Shakhovskoi et al. 2005), the ratios of the large and small cycles turned out to be close to 6.1 and 7.5, respectively. Two cycles (Rostopchina et al. 1999; Bertout et al. 2000) with a ratio close to 7.5 were also detected in the star UXOri itself. It should be noted that these values are still determined from observations not very accurately, because the series of photometric observations are still insufficiently long in a number of cases. Nevertheless, the closeness of all three period ratios to the theoretical period ratios $P_2 : P_1$ given in the table is immediately apparent. This suggests that the cyclic activity of at least some UX Ori stars can actually result from their binarity.

It should be noted that another object with bimodal brightness oscillations exists among the variable stars whose brightness varies periodically. This is the carbon star V Hya. A detailed study of its variability by Knapp et al. (1999) showed that out of its two observed periods ($P_1 = 530^d$ and $P_2 = 6000^d$), the short period is attributable to stellar pulsations, while the long period is related to the star's binarity and is attributable to the eclipses by dust rotating in the orbit together with the secondary component. Some of the Herbig Ae stars, which the family of UX Ori stars mostly consists of, also exhibit pulsations (see Stahler and Palla (2004) and references therein). However, the period of these pulsations is too short (of the order of one hour) and, for this reason, they cannot be involved in producing the bimodal brightness oscillations observed in these stars. Therefore, if the hydrodynamic processes in young binary systems considered above are responsible for these oscillations,

then the shorter of the two periods corresponds to the orbital period.

This makes it possible to estimate the amplitude of the stellar radial velocity variations caused by the orbital motion of the companion. Thus, for example, the shorter of the two periods for CQ Tau is 2.7 yr. The mass of this star was estimated by Rostopchina (1999) to be about 1.5 $M_\odot$. If the above period corresponds to the orbital period of a companion with a mass equal, for example, to 1/5 of the mass of CQ Tau, then the amplitude of the stellar radial velocity variations in this case will be about 10 km/s. Although the absorption lines in the spectra of UX Ori stars are broadened by rapid rotation and are severely distorted by variable circumstellar absorption lines (Grinin et al. 2001), an attempt can be made to measure these stellar radial velocity variations.

The deficit of infrared radiation in the energy distribution (in the near infrared) due to the presence of a matter-free central gap in the disk could be other evidence for the binarity of a star. However, this observational test cannot be considered quite reliable, because much of the near-infrared radiation from the circumstellar disks originates near the dust evaporation zone. According to present views (Natta et al. 2001), the circumstellar disks of young stars are puffed up near this zone, producing excess infrared radiation compared to the standard disk model. Concurrently, this puffing-up produces a shadow zone in the disk (Dullemond et al. 2001), causing a reduction in the infrared radiation at longer wavelengths. The existence of a shadow zone is similar in its observational manifestations to the existence of a matter free zone. Therefore, it is very different to obtain direct observational evidence for the binarity of UX Ori stars by measuring their radial velocities or from the infrared energy distribution. Interferometric observations with large interferometer telescopes like ALMA will probably play an important role in solving this problem.

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Table 1: Parameters of the binary models.

Model	e	M_2	c	P_2/P_1
1	0.3	0.7	0.05	4.73±0.07
2	0.5	0.7	0.05	5.93±0.06
3	0.7	0.7	0.05	6.77±0.14
4	0.5	1.0	0.08	5.97±0.01
5	0.5	1.0	0.05	6.56±0.10
6	0.5	0.4	0.05	5.19±0.16
7	0.1	0.7	0.05	—
8	0.5	1.0	0.02	5.43±0.11
9	0.5	0.2	0.05	—

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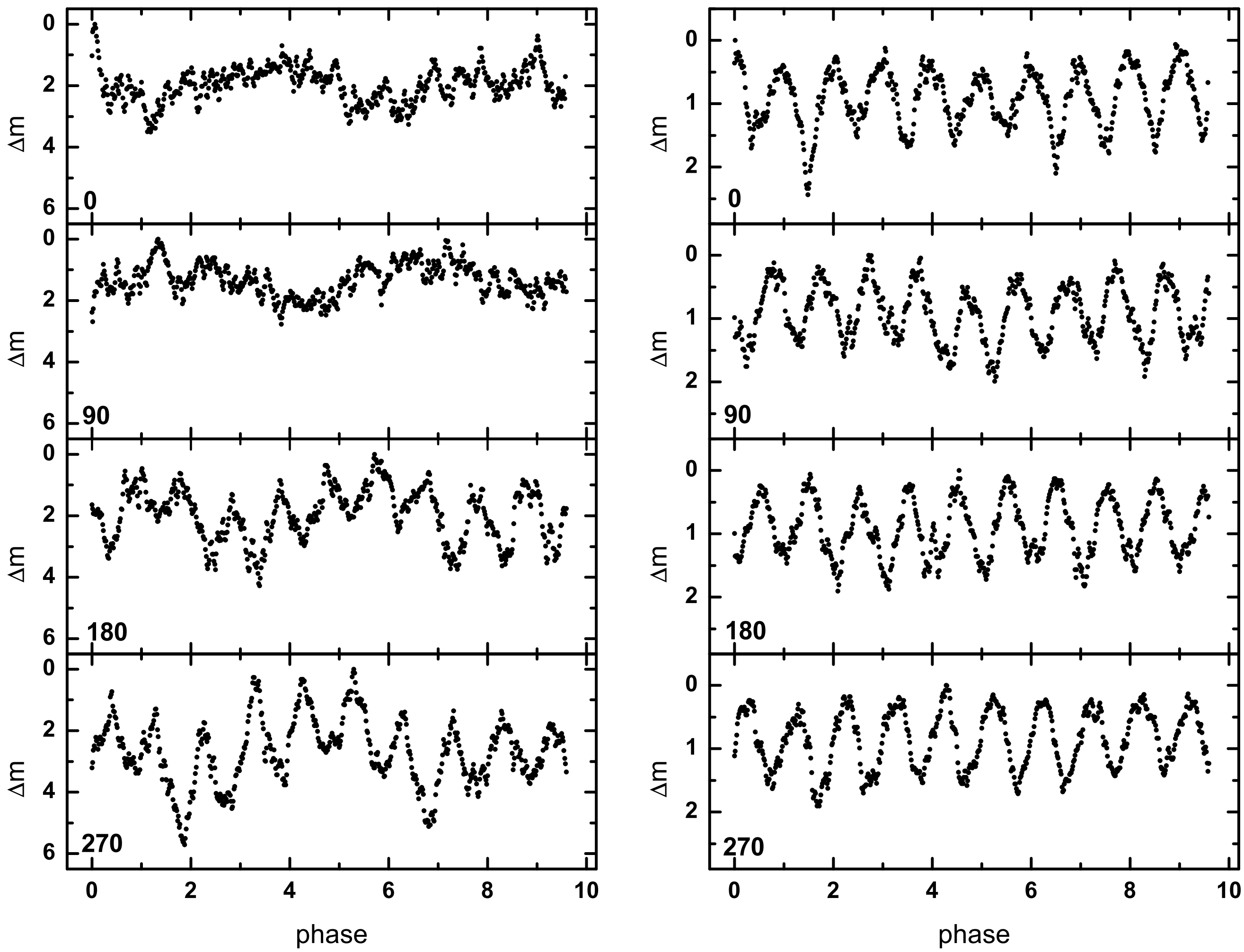

Figure 1: Bimodal brightness oscillations in model 1 (warm disk, e = 0.3, q = 0.35): (a) the line of sight lies in the orbital plane and (b) the disk is inclined at an angle of 10° to the line of sight. The angle that characterizes the position of the apsidal line relative to the observer is indicated in the lower left corner of each panel.

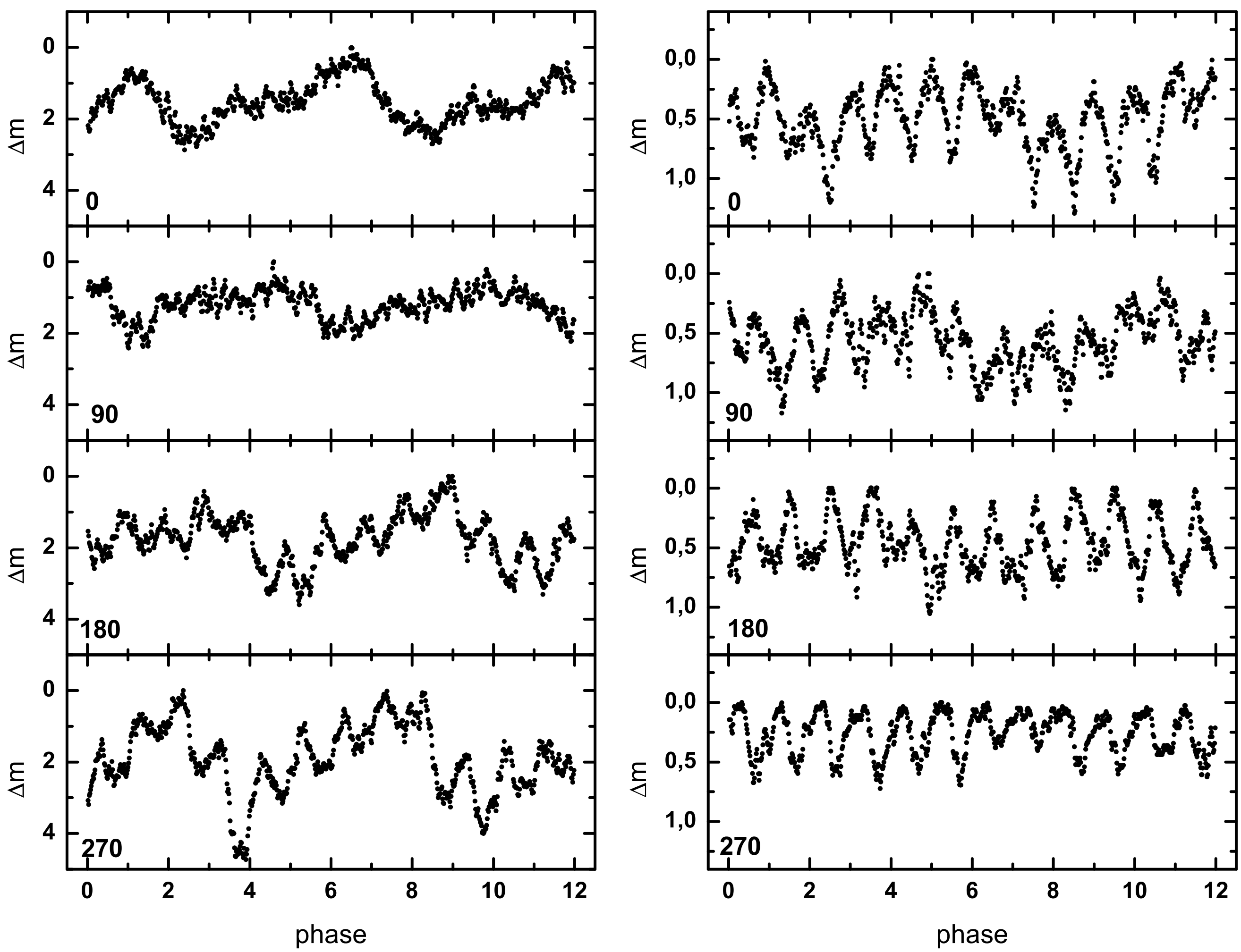

Figure 2: Same as Fig. 1 for model 2 (warm disk, $e = 0.5$, $q = 0.35$).

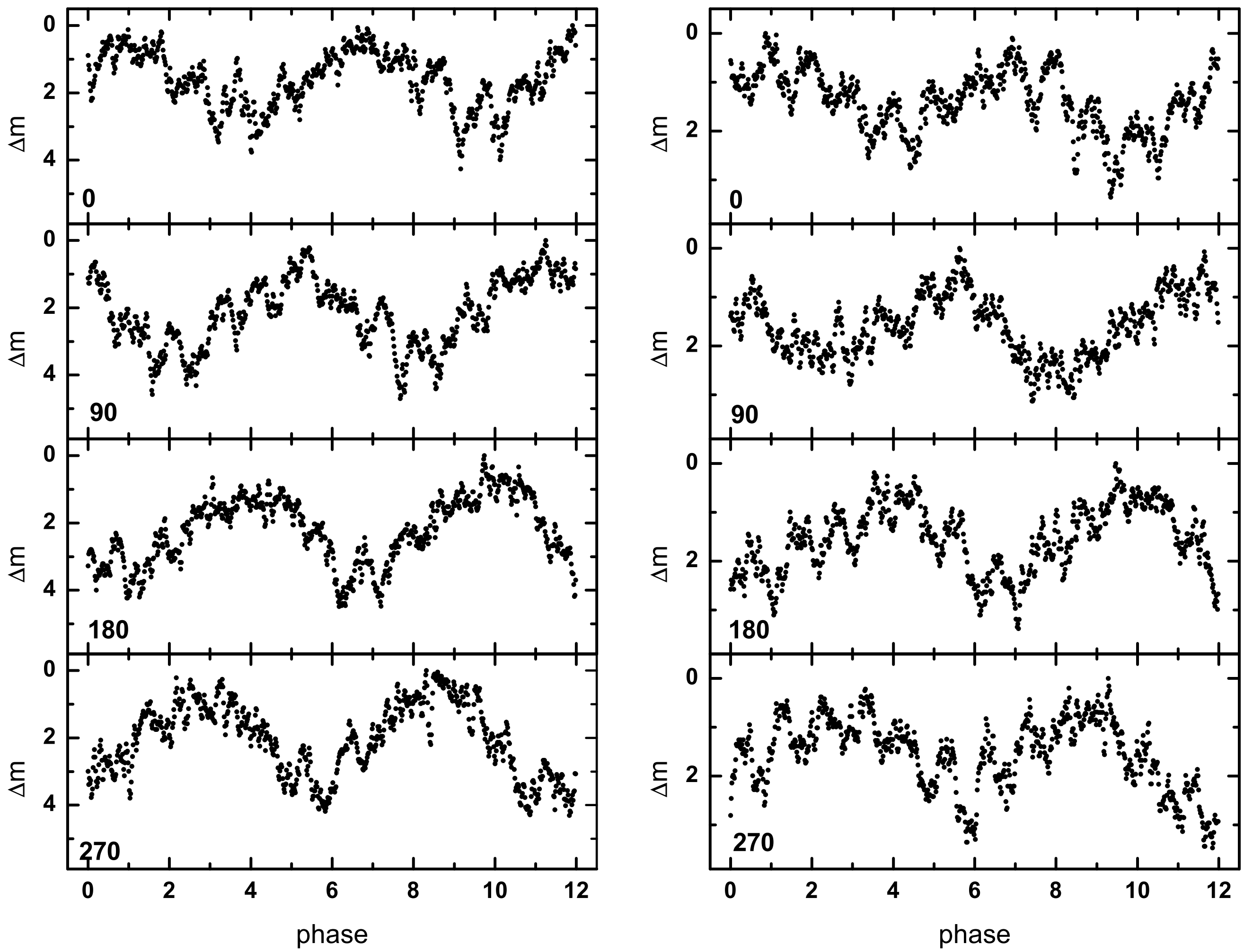

Figure 3: Same as Fig. 1 for model 4 (hot disk, $e = 0.5$, $q = 0.5$). The light curves in the right part of the panel were constructed for the case where the orbit was inclined at an angle of $7^{\circ}.5$ to the line of sight.

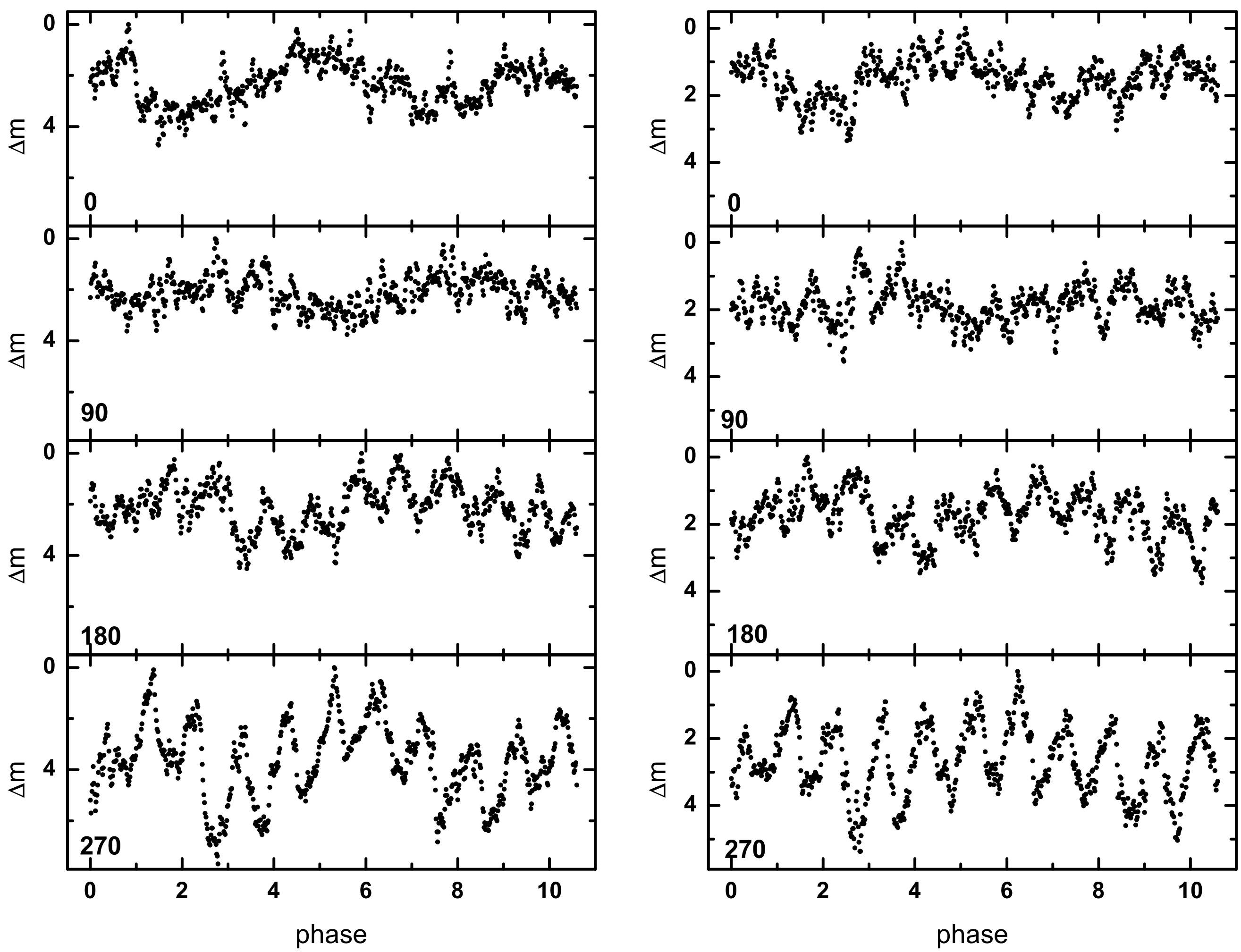

Figure 4: Same as Fig. 1 for model 6 (warm disk, $e = 0.5$, $q = 0.2$). The light curves in the right part of the panel were constructed for the case where the orbit was inclined at an angle of 5° to the line of sight.

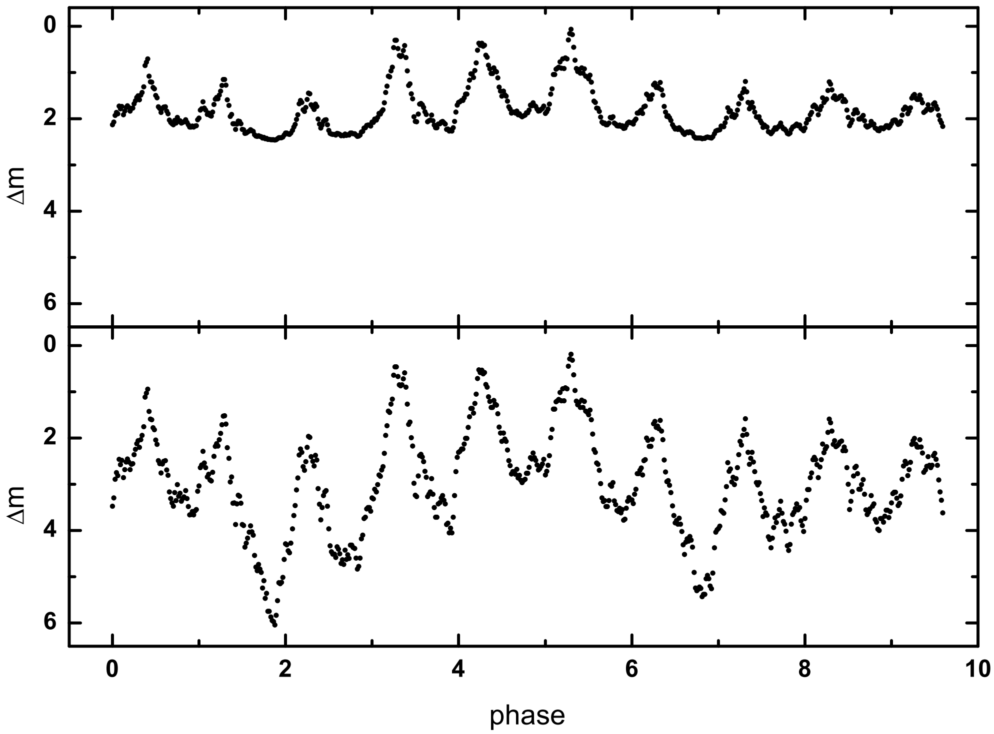

Figure 5: Light curves for model 1: the line of sight lies in the orbital plane and makes an angle of 270° with the apsidal line. The plot illustrates the influence of scattered light on the brightness modulation of the binary system: (a) $I_{sc} = 0.1\, I_*$ and (b) $I_{sc} = 0$.